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Post et al.

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(54) **CABLE-DRIVEN ADDITIVE MANUFACTURING SYSTEM**

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(51) **Int. Cl.**

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B28B 1/00	(2006.01)
E04B 1/35	(2006.01)
B33Y 10/00	(2015.01)

(52) **U.S. Cl.**
CPC ***B28B 1/001*** (2013.01); ***E04B 1/3505*** (2013.01); *B33Y 10/00* (2014.12); *B33Y 30/00* (2014.12); *E04B 2001/3588* (2013.01)

(58) **Field of Classification Search**
CPC B29C 64/227; B29C 64/106; B29C 64/30; B29C 64/209; B66C 13/08; E04B 1/16
USPC 264/31, 32, 22, 34, 35
See application file for complete search history.

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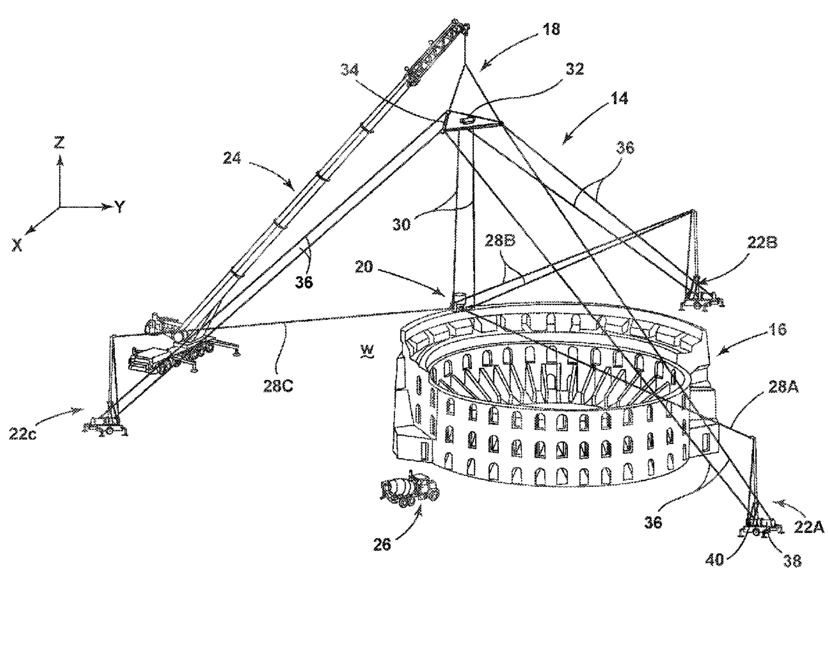
(57) **ABSTRACT**

A cable-driven additive manufacturing system includes an end effector configured for linear translation within a three-dimensional workspace, an aerial hoist suspending the end effector by at least one suspension cable, a plurality of base stations disposed below the aerial hoist, and control cables running from each of the base stations to the end effector.

20 Claims, 8 Drawing Sheets



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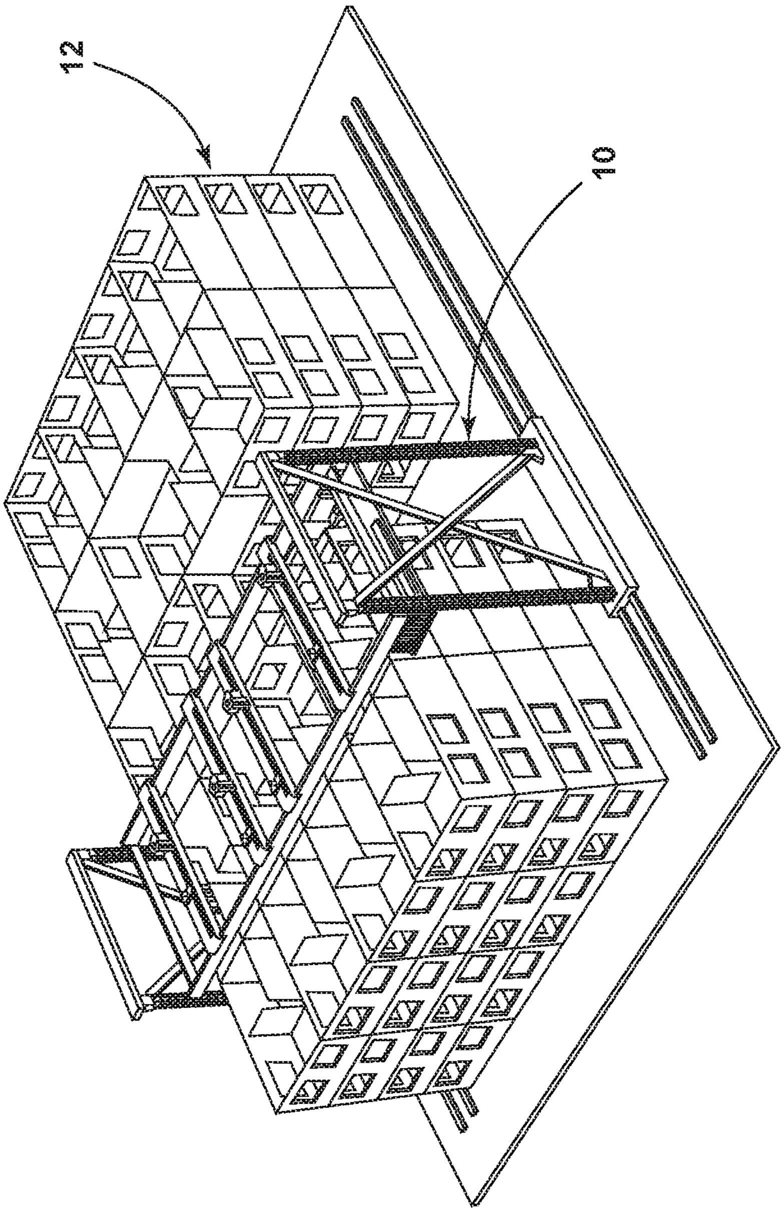

FIG. 1 (PRIOR ART)

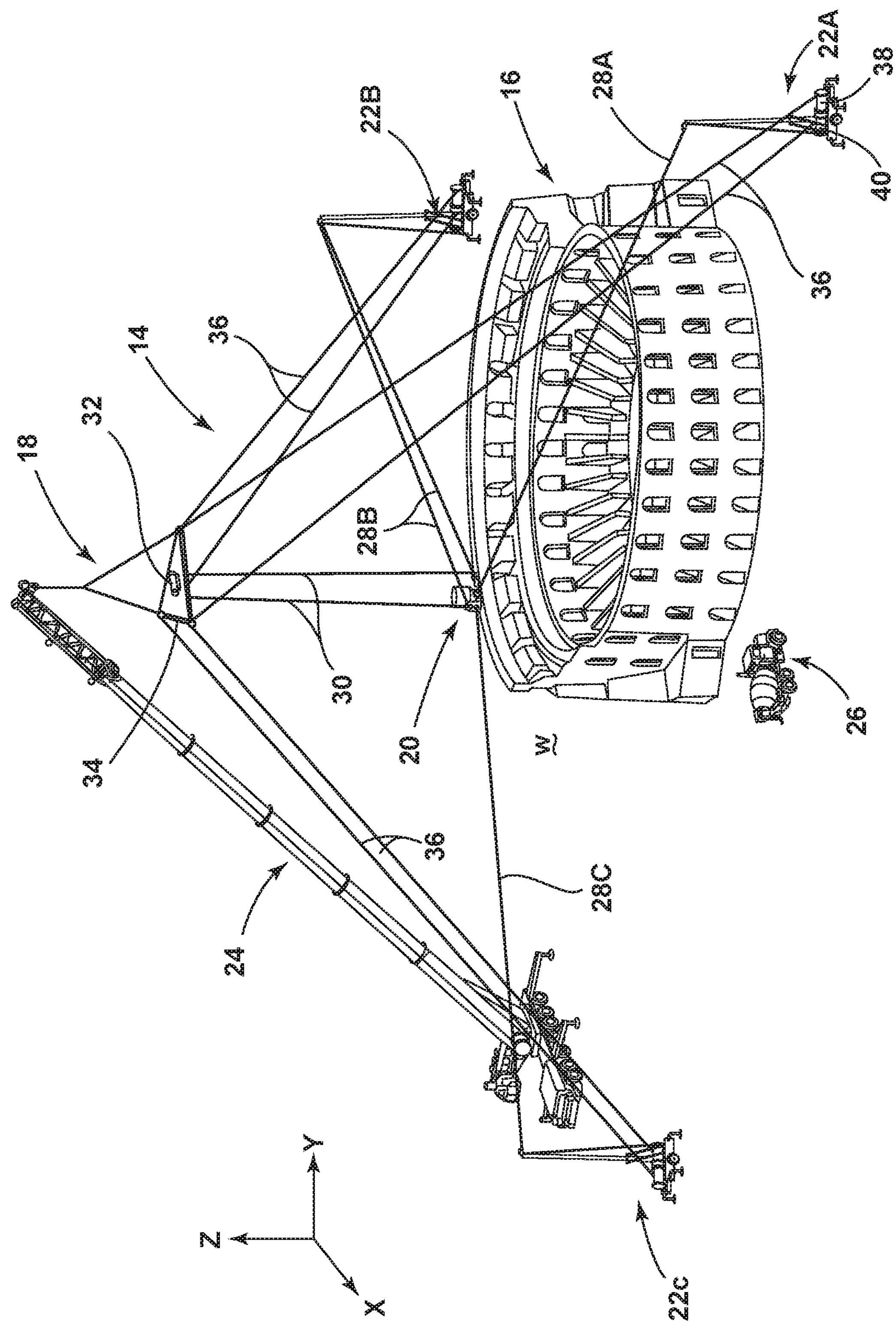

FIG. 2

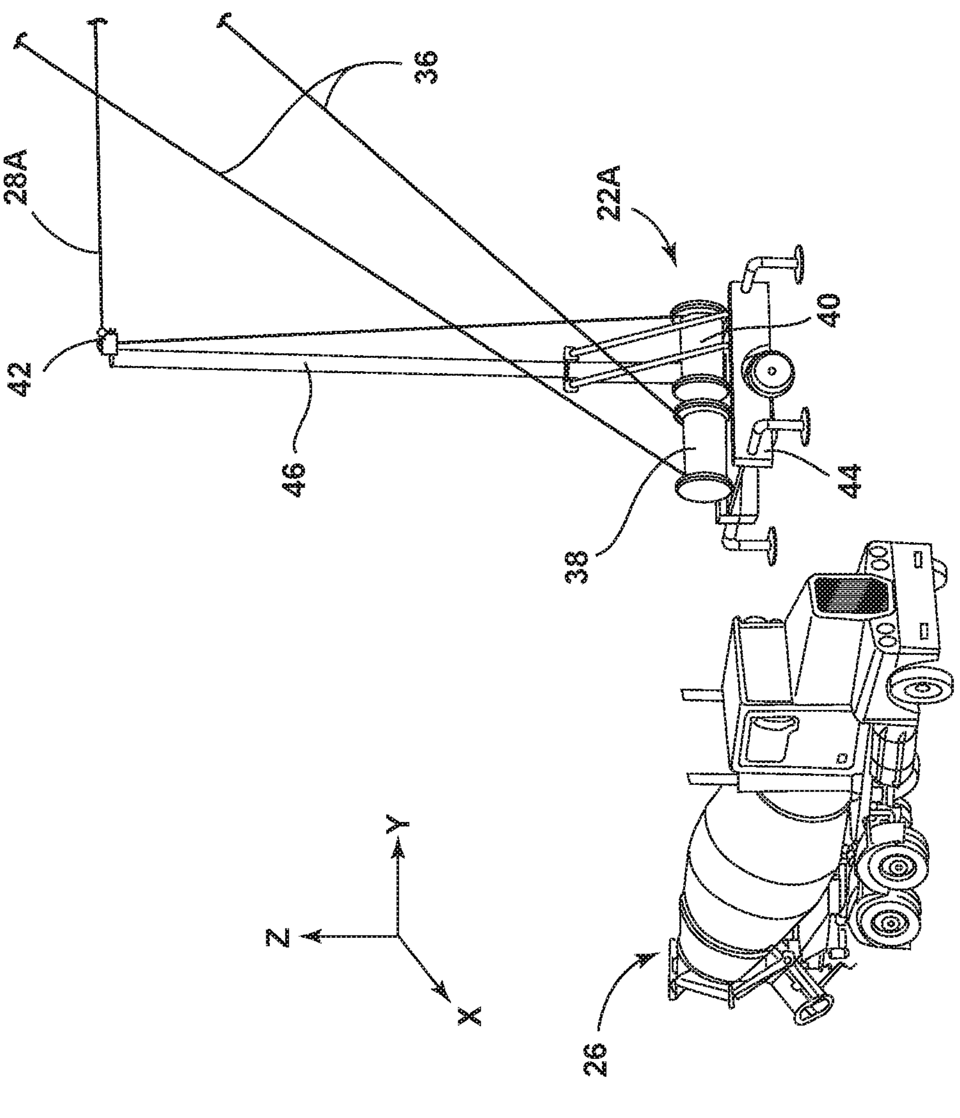

FIG. 3

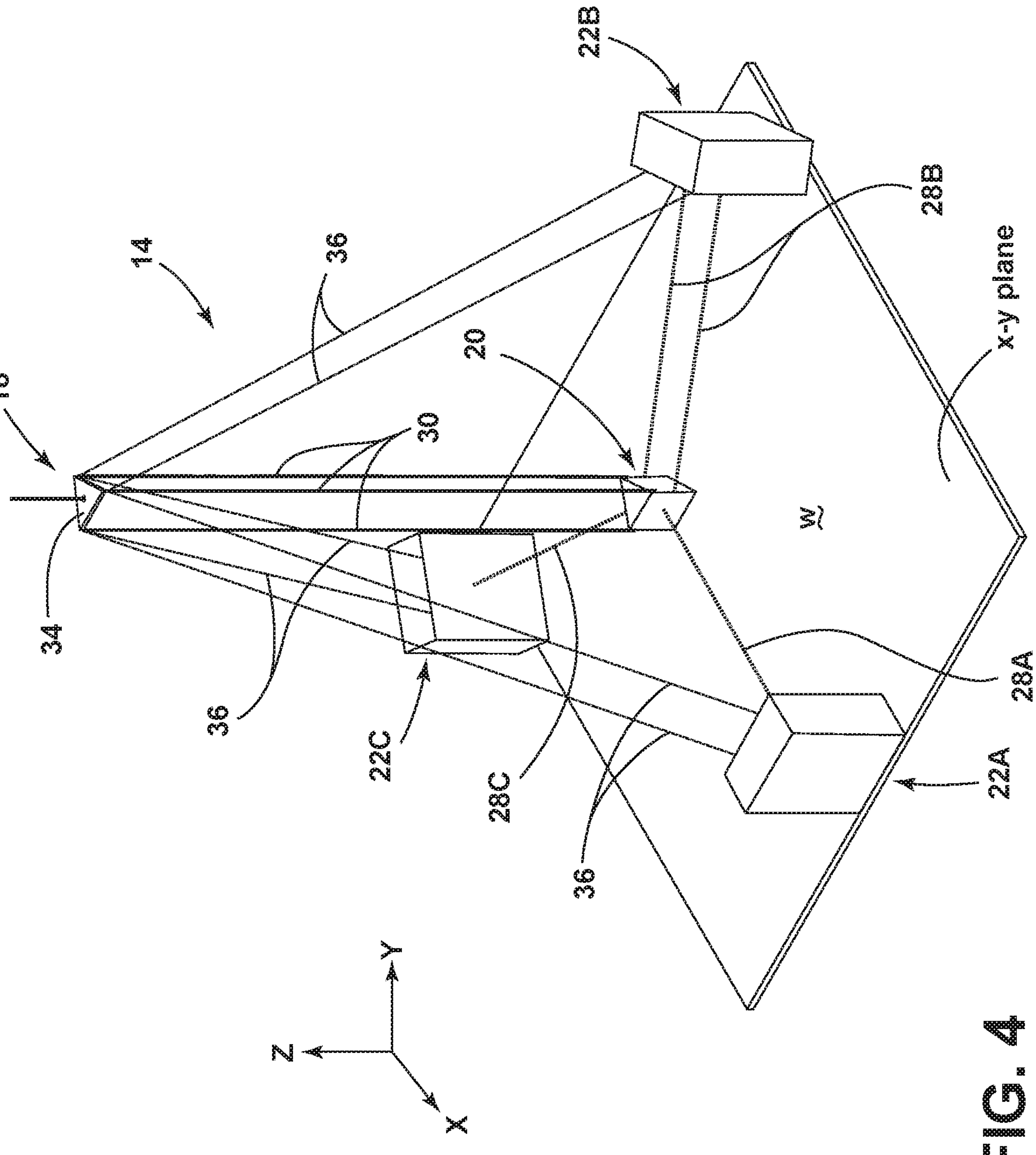

FIG. 4

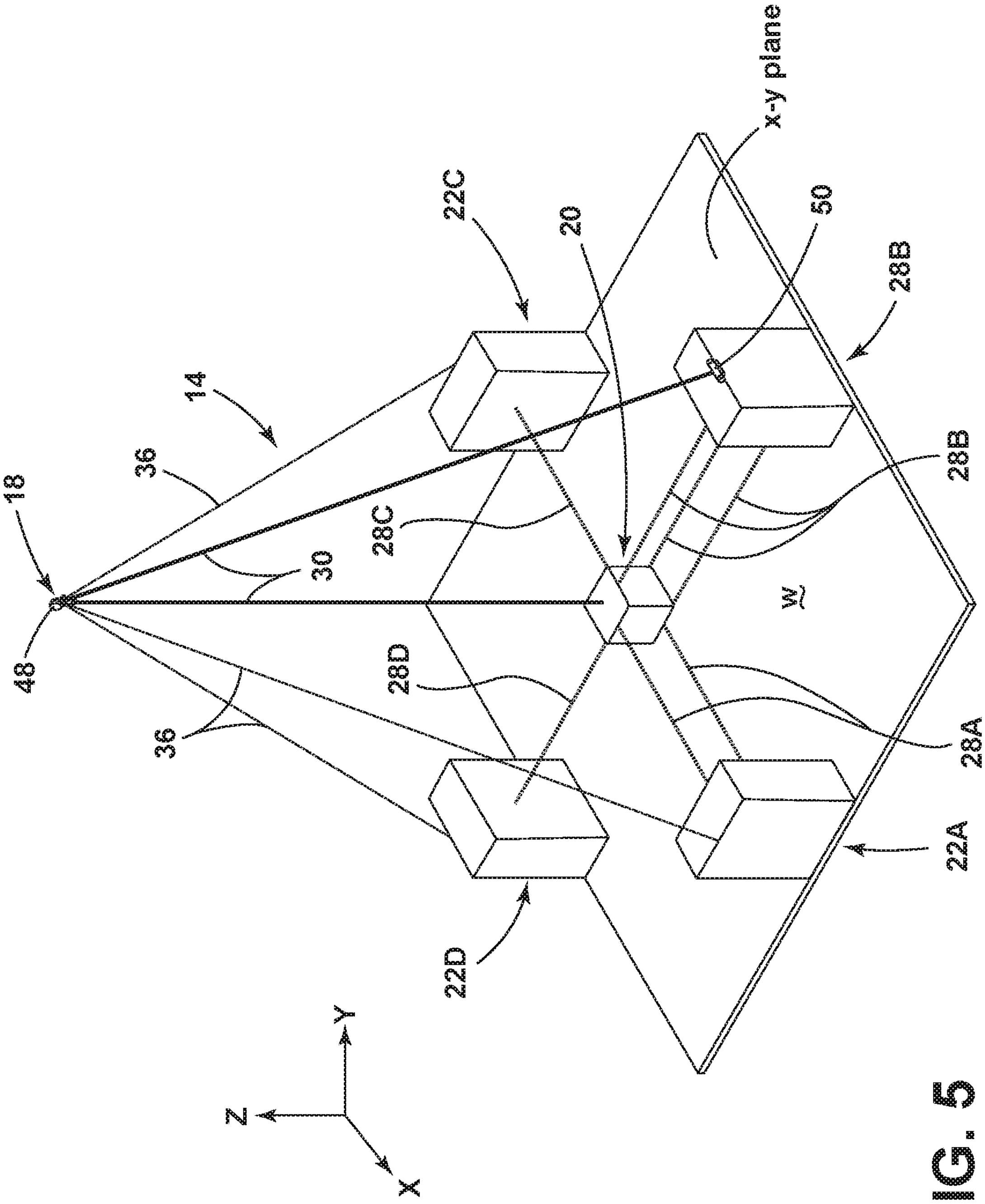
22C
20
50
x-y plane
28B
14
18
36
28B
28C
30
48
w
28D
36
28A
22A
22D
Y
Z
X

FIG. 5

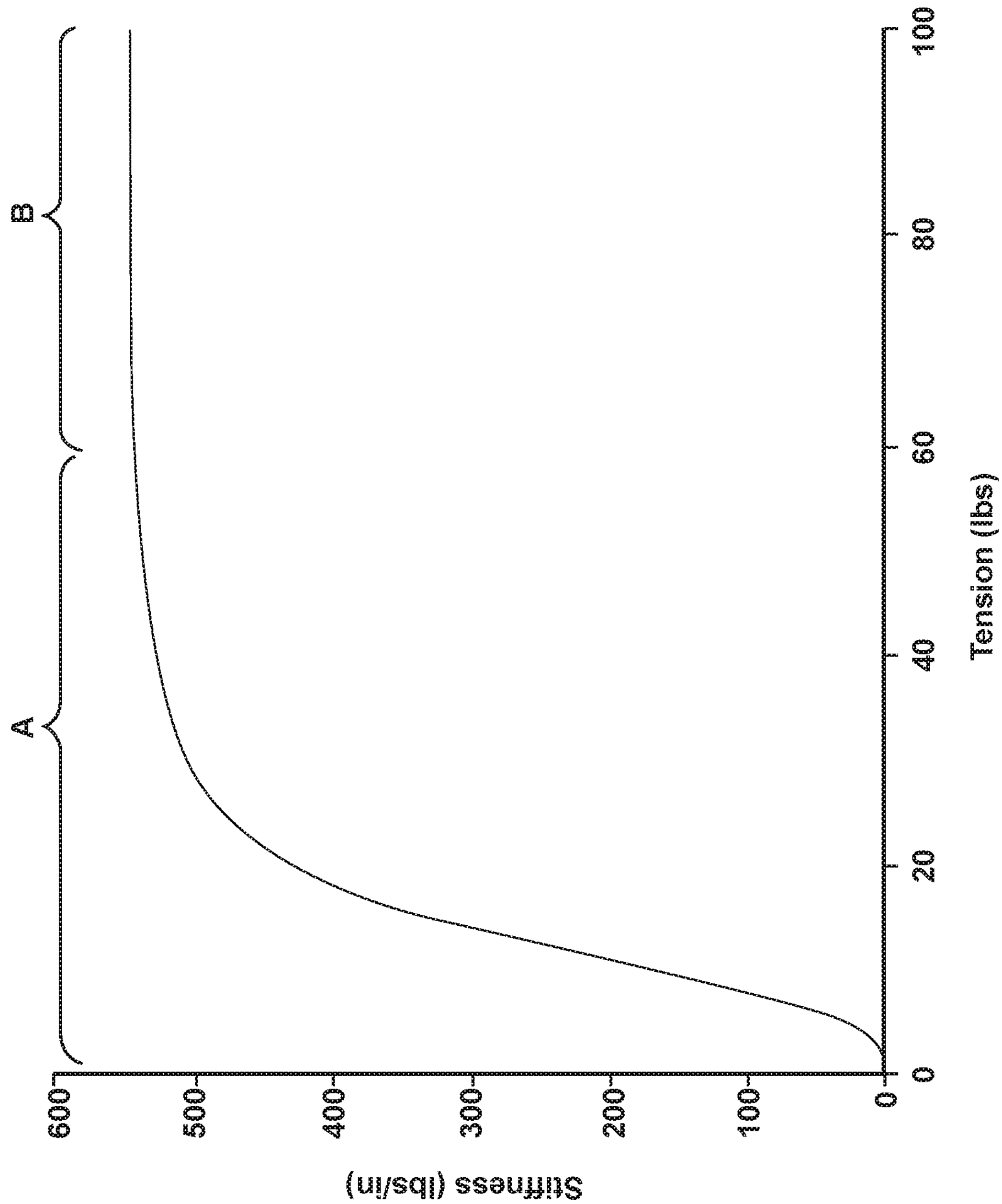
A
B
Stiffness (lbs/in)
Tension (lbs)
0
100
200
300
400
500
600
0
20
40
60
80
100

FIG. 6

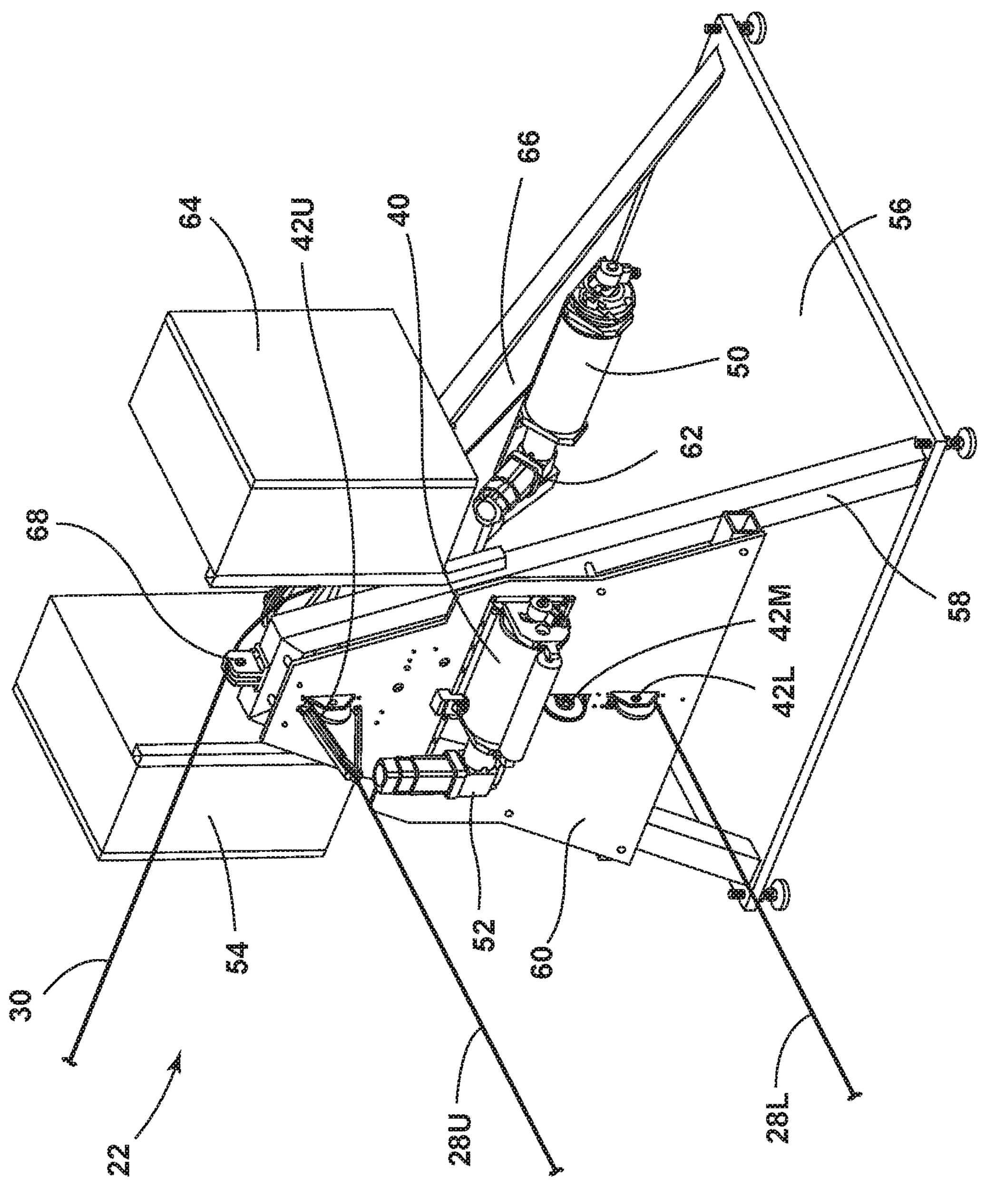

FIG. 7

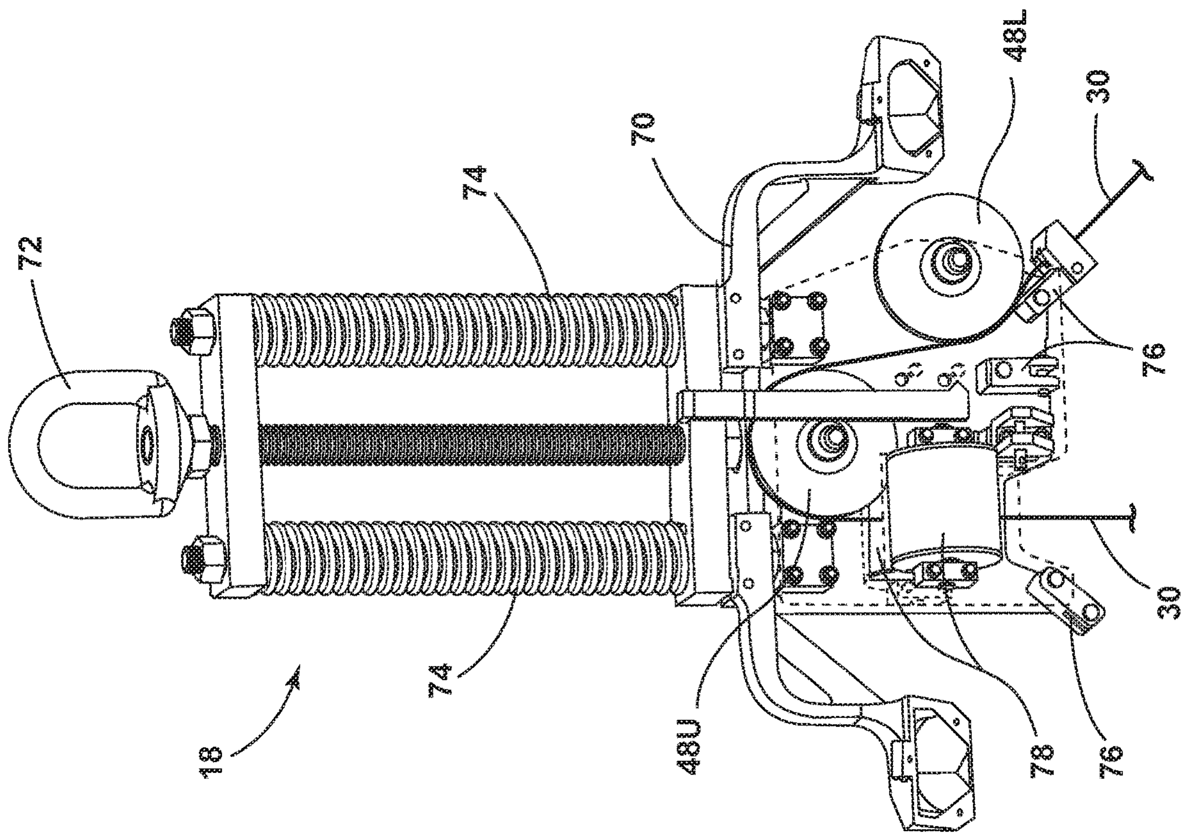

FIG. 8

CABLE-DRIVEN ADDITIVE MANUFACTURING SYSTEM

CROSS-REFERENCE TO RELATED APPLICATION

This application claims the benefit of U.S. Provisional Application 62/657,020, filed Apr. 13, 2018, the disclosure of which is hereby incorporated by reference in its entirety.

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH AND DEVELOPMENT

This invention was made with government support under Contract No. DE-AC05-00OR22725 awarded by the U.S. Department of Energy. The government has certain rights in the invention.

BACKGROUND OF THE INVENTION

The present invention relates to additive manufacturing systems and methods for on-site additive manufacturing of buildings and other constructions.

Concrete additive manufacturing, or 3D printing, has taken off around the world because it is a relatively cost effective material with desirable material properties. For example, WinSun, a Chinese engineering company, has additively manufactured concrete buildings from recycled construction materials. WinSun has fabricated 10 homes in 24 hours by printing the pieces of a structure at one location, and assembling them at an off-site location. In Europe, Swiss company LafargeHolcim teamed up with French start-up, XtreeE, to print Europe's first structural, load-bearing element from concrete. Lastly, the United States Army Corps of Engineers (USACE) has developed an additive manufacturing process that fabricates unique concrete structures through a project called Automated Construction of Expeditionary Structures (ACES).

Construction contributes significantly to harmful emissions, and construction of a typical single-family home generates a waste stream of about 3 to 7 tons, for example. Although concrete creation is an energy intensive process, additive manufacturing allows structures to be fabricated in such a way that material is only deposited where necessary, which leads to much less material waste when comparted to traditional construction practices. Additive manufacturing also enables the fabrication of unique geometries that cannot be achieved through traditional methods. Any departure from standard rectilinear design significantly increases the cost of conventional construction. Additive manufacturing will allow customized designs to be created while saving energy and reducing waste.

To date, all concrete additive manufacturing is completed using gantry systems, which makes fieldability extremely limited. FIG. **1** shows a prior art example of a gantry system **10** fabricating a concrete building **12**. Gantry systems require complicated set up and extensive site preparation to function properly.

On-site fabrication of structures has been demonstrated as a viable construction technique, regardless of suspension system type, but there are a few barriers that have kept on-site fabrication from becoming commercially implemented. Current barriers include: (1) 3D printed concrete structures are not as aesthetically appealing as current facade materials; (2) reinforcing the fabricated structure may be time consuming; (3) laying concrete masonry blocks is currently faster and cheaper than printing concrete; and (4) extensive construction site preparation is required for a gantry system to operate. Accordingly, there remains a continued need for improved large-scale, fieldable additive manufacturing systems.

SUMMARY OF THE INVENTION

An improved large-scale, fieldable or easily transportable additive manufacturing system is provided. Improved methods for on-site additive manufacturing of buildings and other constructions are also provided.

In one aspect of the invention, a cable-driven additive manufacturing system is provided.

In one embodiment, the cable-driven additive manufacturing system includes an end effector configured for linear translation within a three-dimensional workspace along an x-axis, y-axis, and a z-axis, an aerial hoist suspending the end effector within the three-dimensional workspace by at least one suspension cable, an aerial cable winder configured to control linear translation of the end effector along the z-axis, a plurality of motion-control base stations disposed below the aerial hoist and configured to control linear translation of the end effector in an x-y plane defined by the x-axis and the y-axis, each motion-control base station comprising a base station cable winder, a plurality of motion-control cables, at least one of the plurality of motion-control cables running from each of the base station cable winders to the end effector, at least one tension-control base station, and at least one tension-control cable running from the tension-control base station to the end effector.

The embodiments of the invention eliminate the need for a gantry system or other large framework for the large-scale additive manufacturing, and will eliminate the need for extensive site preparation, which has prevented on-site additive manufacturing from becoming commercially viable. Implementing a mechanized form of construction also reduces labor costs. On-site construction allows for shorter construction time, reduced site disruption, more consistent quality, flexibility of site use, and financial savings. Embodiments of the system offer a significant improvement over existing concrete methods because of the ease and versatility of set up and energy efficiency achieved through additive manufacturing.

These and other features and advantages of the present invention will become apparent from the following description of the invention, when viewed in accordance with the accompanying drawings and appended claims.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a schematic illustration of a prior art gantry system fabricating a concrete building;

FIG. **2** is a schematic illustration of a cable-driven additive manufacturing system according to one embodiment of the invention fabricating a concrete building;

FIG. **3** is a schematic illustration of a base station for the cable-driven system of FIG. **2**, with a conventional concrete truck shown for scale;

FIG. **4** is a schematic illustration of another embodiment of a cable configuration for the cable-driven additive manufacturing system;

FIG. **5** is a schematic illustration of yet another embodiment of a cable configuration for the cable-driven additive manufacturing system;

FIG. **6** is a graphical representation of a composite stiffness value that is dependent upon cable tension for a ⅛-inch 7×19 steel wire rope cable having a span of 17 ft;

FIG. **7** is an isometric view of one embodiment of a base station for the cable-driven additive manufacturing system; and

FIG. **8** is an isometric view of one embodiment of an aerial hoist for the cable-driven additive manufacturing system.

DETAILED DESCRIPTION OF THE CURRENT EMBODIMENT(S)

Disclosed is a large-scale cable-driven system for the deposition of structures from concrete or other cementitious material. The system is designed to be easily fieldable for use at an outdoor work site. Smaller-scale and/or indoor implementation are also contemplated.

A cable-driven additive manufacturing system **14** in accordance with a first embodiment of the present invention is shown in FIG. **2**. The cable-driven system **14** is shown fabricating a concrete building **16** in FIG. **2**. The cable-driven system **14** is a large-scale, fieldable or easily transportable concrete deposition system, and includes an apex or aerial hoist **18**, an end effector **20** including a printing or deposition head, and a plurality of base stations **22**A, **22**B, **22**C. The cable-driven system **14** can be implemented with existing construction equipment. For example, a conventional crane **24** can be used to suspend the aerial point **18**. Other equipment which can be used to suspend the aerial point **18** include, but are not limited to, a lighter-than-air balloon or a roof of an inflatable building. This implementation allows quick setup onsite with minimal site preparation. For scale, a conventional concrete truck **26** is also shown in FIG. **2**.

The end effector **20** is positioned in and maneuvered within a three-dimensional (3D) workspace W of the worksite. The base stations **22**A, **22**B, **22**C are located about the perimeter of 3D workspace W. A Cartesian coordinate system can be conceptually applied to 3D workspace W as shown in FIG. **2**, and the system **14** controls linear translation of the end effector **20** along the x-axis, y-axis, and z-axis.

The end effector **20** can be any device operable to deposit concrete or other cementitious material onto the worksite. Generally, the end effector **20** can include a nozzle configured to selectively deposit the material at predefined locations based on the position of the end effector **20** within the 3D workspace W. Concrete or other cementitious material can be held in a reservoir or hopper carried by the end effector and supplied to the nozzle. Material can be supplied to the reservoir manually or automatically. For manual supply, the reservoir or hopper can be periodically refilled as material is used to fabricate a structure. Automatic supply can be done with a concrete pumping truck. A boom of the pumping truck can extend above the end effector **20** and a flexible hose can run from the extended boom to the reservoir or hopper, and provide a continuous flow of material for deposition.

In the embodiment shown, the system **14** includes three base stations **22**A, **22**B, **22**C. The base stations **22**A, **22**B, **22**C are mobile for transport to and from the worksite, but are statically arranged about the perimeter of the 3D workspace W during use. Adjustable cables **28**A, **28**B, **28**C run from each base station **22**A, **22**B, **22**C to the end effector **20**. In other embodiments, the system **14** may include one or more additional base stations. Similarly, in other embodiments, one or more additional adjustable cables may be associated with any of the base stations.

Each set of adjustable cables **28**A, **28**B, **28**C may be routed from a base station **22**A, **22**B, **22**C and releasably secured to the end effector **20** in a manner that applies tension to the end effector **20** within the 3D workspace W. The cables **28**A, **28**B, **28**C can be tensioned to lie substantially parallel to the x-y plane of the 3D workspace W. In operation, these cables **28**A, **28**B, **28**C typically diverge some amount from the x-y plane and so may be up to 5 degrees, or alternatively up to 10 degrees, or alternatively up to 20 degrees from parallel to the x-y plane during operation. The adjustable cables **28**A, **28**B, **28**C may be adjustably extended and retracted from the base stations **22**A, **22**B, **22**C in a coordinated fashion to maneuver the end effector **20** within the 3D workspace W. As shown, at least one of the base stations **22**B has two associated cables **28**B, and the cables **28**B may be generally parallel to each other, and may be controlled to have similar or identical lengths spanning between the base station **22**B and end effector **20** during operation.

At least one adjustable suspension cable **30** runs from the aerial hoist **18** to the end effector **20**. At least a portion of the suspension cable **30** extends generally vertically to hang the end effector **20** within the 3D workspace W. The system **14** includes a single aerial hoist **18** having at least one cable winder **32** or the like which controls the z-axis motion of the end effector **20**. The suspension cable **30** can be adjustably extended from the cable winder **32** and retracted back on the cable winder **32**. A motor (not shown) or the like can control the cable winder **32**. In other embodiments of the system, the system can comprise more than one aerial hoist **16**. However, in a fieldable system, it is desirable to keep the number of aerial winding points to a minimum to simplify setup onsite.

The aerial hoist **18** forms an apex of the cable configuration for the cable-driven system **14**. The base stations **22**A, **22**B, **22**C, or at least the cables **28**A, **28**B, **28**C running from the base stations **22**A, **22**B, **22**C to the end effector **20**, are disposed below the aerial hoist **18**. To integrate the system **14** with existing construction equipment or other equipment, the crane **24** or other suspender is not part of the motion system. Instead, the crane **24** or other suspender acts as a static hoist point for the aerial hoist **18**. Because the crane **24** or other suspender merely provides a hoist point for the system **14**, the cable-driven system **14** can be integrated with any crane or other suspender that meets the necessary height and load requirements.

In the illustrated embodiment, the aerial hoist **18** comprises a platform **34** that supports the cable winder **32**. The end effector **20** is suspended from the platform **34** by the suspension cables **30**. In the illustrated embodiment, the end effector **20** is suspended below the fixed platform **34** by two parallel suspension cables **30** that ensure the end effector **20** remains perpendicular to the deposition surface. The suspension cables **30** can be adjusted so that their length is always identical, and can be controlled via one common cable winder, or separate cable winders may be provided.

The suspended platform **34** is secured with guy-wires **36** to the base stations **22**A, **22**B, **22**C. Alternatively, the guy-wires **36** can extend from the platform **34** to the ground or another static point. Cable winders **38** or the like for the guy-wires **36** can be provided on the base stations **22**A, **22**B, **22**C, or can be provided separately from the base stations **22**A, **22**B, **22**C. The guy-wires **36** can be adjustably extended from the cable winders **38** and retracted back on the cable winders **38**. A motor (not shown) or the like can control each cable winder **38**. The motors can be controlled in a coordinated fashion to stay the platform **34** at a desired location within the 3D workspace W.

Referring to FIG. **3**, each base station **22**A, **22**B, **22**C includes at least one cable winder **40** or the like which controls the motion of the end effector **20** in the x-y plane. In FIG. **3**, base station **22**A is shown, but this applies for all base stations **22**A, **22**B, **22**C of FIG. **2**. Each adjustable cable **28**A, **28**B, **28**C can be adjustably extended from one of the cable winders **40** and retracted back on the cable winder **40**. For the base station **22**B with two associated cables **28**B (FIG. **2**), the cables **28**B can be controlled via one common cable winder **40**, or separate cable winders may be provided. A motor (not shown) or the like can control each cable winder **40**. The motors can be controlled in a coordinated fashion to maneuver the end effector **20** within the 3D workspace W, relative to the x-y plane. It is noted that as the end effector **20** is moved in the x-y plane, the suspension cables **30** will move as well.

In one embodiment, a central controller can be in operative communication with each aerial and base cable winder **32**, **40**, or more specifically each cable winder motor, to provide coordinated control and maneuvering of the end effector **20**. The central controller can maneuver the end effector **20** in response to operator controls and end effector position control algorithms. Alternatively or additionally, the central controller can maneuver the end effector **20** in an automated or semi-automated fashion in response to a pre-programmed building plan based on position control algorithms. The central controller may include any suitable controller, including any suitable combination of a CPU, processor, microprocessor, computer, software, firmware, and any combination over various common peripheral devices or components associated with such items. Similarly, any controller associated with an individual motor or group of motors may include any suitable controller, including any suitable combination of a CPU, processor, microprocessor, computer, software, firmware, and any combination over various common peripheral devices or components associated with such items.

Optionally, the base stations **22**A, **22**B, **22**C can include at least one pulley **42**, multiple pulleys, or another suitable cable guide which route the cables **28**A, **28**B, **28**C to change the direction of the force applied by the cables **28**A, **28**B, **28**C. In FIG. **3**, the base station **22**A includes a support **44** adapted to be statically fixed to the ground or otherwise anchored at the worksite, and a vertical support post **46** extending upwardly from the support **44**. The pulley **42** can be provided on the vertical support post **46**, preferably at the top of the vertical support post **46**. From the winder **40** to the pulley **42**, the cable **28**A can run generally parallel to the post **46**, and from the pulley **42** to the end effector **20**, the cable **28**A can run generally orthogonally to the post **46**.

To provide motion of the end effector **20** within the 3D workspace W along the x-, y-, and z-axes, three active actuators are required. For example, the cable winders **32**, **40** of the aerial hoist **18** and two of the base stations **22**A, **22**B can effectively move the end effector **20** within the x-y plane of the 3D workspace W. These base stations **22**A, **22**B are motion-control base stations. The third base station **22**C can comprise a passive actuator, such as by having a torque motor operate the winder, and provides tension only. This base station **22**C is a tension-control base station.

The system **14** is always operated in tension to enhance the system stiffness. Cable flexibility is accounted for in the control systems through advanced vibration control techniques like input shaping. Absolute position feedback can be provided by GPS or a laser tracker positioned out of the 3D workspace W ensuring accurate placement of the deposited material.

The base stations **22**A, **22**B, **22**C can be adjustable to allow the end effector **20** to print taller structures without interfering with the cables **28**A, **28**B, **28**C. Generally, the point at which the cables **28**A, **28**B, **28**C extend in the x-y plane away from the base stations **22**A, **22**B, **22**C need to be able to raise up as the printed structure gets taller. In one embodiment, at least a portion of the base stations **22**A, **22**B, **22**C can telescope to allow the end effector **20** to print taller structures without interfering with the cables **28**A, **28**B, **28**C. For example, the vertical support post **46** can be a telescoping vertical support post **42** that adjusts the height of the pulley **42**. In another example, the support **44** can telescope or be otherwise adjustable to adjust the height of the pulley **42** while maintaining a fixed distance between the cord winder **40** and pulley **42**. Non-telescoping adjustment mechanisms can be used as well, such as using a linear rail to adjust the position of the pulley **42** or another portion of the base stations **22**A, **22**B, **22**C. The adjustability of the base stations **22**A, **22**B, **22**C can also be leveraged when setting up the work site, so that the base stations **22**A, **22**B, **22**C do not need to be disposed on a level site, and can rather be implemented on a variety of terrain, including terrain requiring one base station **22**A, **22**B, **22**C to be disposed higher than another base station **22**A, **22**B, **22**C.

All cables can be releasably secured to the end effector **20** to make setup and takedown of the system **14** more streamlined. The various cables can be wound around their associated cable winders for transportation to a worksite. To set up the system **14** at a worksite, the base stations **22**A, **22**B, **22**C are positioned about the perimeter of the 3D workspace W, and the cables **28**A, **28**B, **28**C are attached to the end effector **20**. Optionally, the base stations **22**A, **22**B, **22**C can be contained on individual trailers, and can simply be driven onto the worksite to the correct position about the perimeter of the 3D workspace W. The aerial suspension cables **30** are also attached to the end effector **20**, and the crane **24** lifts the aerial hoist **18** overhead.

After setup, the system **14** can go through a calibration routine so that the location of the end effector **20** can be tracked through 3D space. The location of the cable winders **32**, **40** on the aerial hoist **18** and base stations **22**A, **22**B, **22**C must also be known in 3D space. A laser-based time-of-flight sensor or laser tracker can be used to locate the cable winders **32**, **40** and base stations **22**A, **22**B, **22**C for initial calibration of the system **14**, and can also be used to locate and track the end effector **20** during material deposition. Alternatively, GPS-based tracking can be used. Other input can be used to control the system **14** as well. For example, encoders on the various cable winders can measure the length of the extended cable.

By definition, any object in 3D space has six degrees for freedom (DOF). In order to fully constrain the end effector **20**, most cable driven systems control all six DOF. However, this requires six independently controlled winders. For most additive manufacturing, only three DOF control is needed. Linear translation is necessary in all three directions; however, the three rotational degrees of freedom are not needed. Instead of controlling the rotational degrees of freedom, it is better to simply freeze them and only control the linear degrees of freedom. By carefully choosing the cable geometry and controlling multiple cables from one winder, this is achieved with the system **14**. By only controlling the three DOF needed, it is possible to make a simpler system. This, in turn, aids in the ease of fieldability.

Furthermore, it is undesirable to over-constrain the system. If there are more cables than are necessary to fully constrain the system, it becomes over-constrained. In an over-constrained system, forces can quickly get quite large, and the demands on the control system are much greater. Thus, it is desirable to have an exactly constrained system.

In one example, the cable configuration of the system includes a single aerial winder that can be held by a standard crane, cable winders and anchor points at a plurality of base stations, a fully and exactly constrained end effector. All rotational degrees of freedom are frozen.

It is also desirable to keep the total number of winders and cable anchor points to a minimum. Furthermore, by concentrating cable winding points and anchor points together, the system **14** can be split into a handful of base stations **22**A, **22**B, **22**C for deployment in the field. These base stations **22**A, **22**B, **22**C can be integrated into a truck or trailer that can simply be driven onto the worksite to the correct position about the perimeter of the 3D workspace W.

FIG. **4** shows another embodiment of a cable configuration for the cable-driven additive manufacturing system **14**. The system **14** of FIG. **4** can include the various functions and components as described in FIGS. **2**-**3**, and like parts will be identified with like numerals. Many of the components are shown schematically in FIG. **4**. One difference is that three adjustable suspension cables **30** run from the aerial hoist **18** to the end effector **20**, and perform the z-axis motion. These three cables **30** all run off one cable winder **32** (FIG. **2**) or the like located on the platform **34**, so that their length is always identical. This keeps the end effector **20** from tilting, which freezes two rotational DOF of the end effector **20**.

Motion in the x-y plane is controlled by the three cables **28**A, **28**B coming from two of the base stations **22**A, **22**B, or motion-control stations. One of these base stations **22**B has two identical length cables **28**B. This freezes the third rotational DOF of the end effector **20**. The two cables **28**B can share a common cable winder **40**, and can be routed around two different pulleys **42**.

A cable **28**C from the third base station **22**C, or tension-control station, provides tension only. By controlling the tension of its associated cable **28**C, the third base station **22**C provides a force that keeps the other cables **28**A, **28**B in tension. The third base station **22**C does not contribute to the motion of the end effector **20**. Consequently, the system **14** is not over-constrained. The three base stations **22**A, **22**B, **22**C can be disposed in an approximate triangle or in a Y-shape about the 3D workspace W.

FIG. **5** shows yet another embodiment of a cable configuration for the cable-driven additive manufacturing system **14**. The system **14** of FIG. **5** can include the various functions and components as described in the embodiments of FIGS. **2**-**4**, and like parts will be identified with like numerals. Many of the components are shown schematically in FIG. **5**. One difference is that one adjustable suspension cable **30** runs from the aerial hoist **18** to the end effector **20**, and perform the z-axis motion. Two extra cables **28**A, **28**B are applied to the motion-control base stations **22**A, **22**B. One of these base stations **22**B has three identical length cables **28**B. This freezes two rotational DOF of the end effector **20**. The three cables **28**B can share a common cable winder **40**, and can be routed around three different pulleys **42**. The other of these base stations **22**A has two identical length cables **28**A. This freezes the third rotational DOF of the end effector **20**. The two cables **28**A can share a common cable winder **40**, and can be routed around two different pulleys **42**.

Like the cable configuration of FIG. **4**, the cable configuration of FIG. **5** freezes all the rotational DOF but offers several advantages to the previous embodiment. First, by putting more cables in the x-y plane, the stiffness of the system **14** is increased in the x-y plane. Although this sacrifices some of the vertical stiffness, the stiffness in the x-y plane is more important for the system **14** because most of the movement of the end effector **20** will be in this plane. The only vertical or z-axis movement will be in between layers when the end effector **20** is raised by a small increment.

The system **14** is also simplified by eliminating the aerial platform of the aerial hoist **18**. Instead, the aerial hoist **18** can comprise at least one pulley **48**, multiple pulleys, or another suitable cable guide which route the suspension cable **30** to change the direction of the force applied by the cable **30**. With only one aerial cable **30**, it is possible to run the cable **30** over the pulley **48** or another suitable cable guide and down to a cable winder **50** or the like located on one of the base stations **22**B, or provided separately from the base stations **22**A, **22**B, **22**C, **22**D. The pulley **48** is still held up by the crane **24** (FIG. **2**), and is held stationary with three guy-wires **36**. Each of the three guy-wires **36** run from the pulley **48** or elsewhere on the aerial hoist **18** to one of the other base stations **22**A, **22**C, **22**D. Alternatively, the guy-wires **36** can extend from the pulley **48** or aerial hoist **18** to the ground or another static point.

Another difference is that the system **14** has an additional base station **22**D and cable **28**D to provide tension only. The net force to keep the other cables **28**A, **28**B in tension is the vector sum of the tension in these two tension cables **28**C, **28**D. By adjusting the tension of the two tension cables **28**C, **28**D, the net tension vector can by adjusted to some degree to optimize the system **14**. By concentrating cables to four base stations **22**A, **22**B, **22**C, **22**D and one overhead hoist **18**, this system **14** is easily fieldable. The four base stations **22**A, **22**B, **22**C, **22**D can be approximately perpendicular to each other or in an X-shape about the 3D workspace W.

With reference to FIG. **6**, one concern in the design of the system **14** is the effective stiffness of the end effector **20**. The stiffness will affect both the quality of prints and the speed at which material deposition can occur. In a stiffer system, the end effector **20** will deflect less under dynamic loads, leading to a more accurate and repeatable construction. Furthermore, a stiffer system leads to higher natural frequencies, which makes control of the system easier.

As mentioned above, the cable layout of the cable-driven system **14** disclosed in FIG. **5** increases the stiffness of the system **14** in the x-y plane, as this is the plane in which most of the motion of the end effector **20** occurs. Cable selection and cable tension also affect the stiffness of the system **14**. In selecting a cable and the required tension for the system **14**, the effects of catenary sag must be considered. A cable span under gravity sags in a well-known and well-studied shape called a catenary. The amount of catenary sag is dependent upon the amount of tension in the cable. This results in significant non-linearities in the stiffness of cables.

FIG. **6** is a graphical representation of a composite stiffness value that is dependent upon cable tension for a ⅛-inch (3.18 mm) 7×19 steel wire rope cable having a span of 17 ft (5.18 m). The composite stiffness value was determined by combining the non-linear stiffness produced by catenary sag of the steel wire cable along with the elastic stiffness of the steel wire cable. As shown in FIG. **6**, there is point where the contribution of the catenary sag to the stiffness becomes negligible, and the stiffness remains approximately constant with increasing tension. Cable stiffness can be classified into a non-linear range A, in which stiffness increases with increasing tension and a linear range B, in which stiffness remains approximately constant with increasing tension. This behavior is consistent across different cable types and sizes.

In certain embodiments, the system **14** is preferably operated to maintain the cables **28**A, **28**B, **28**C, **28**D in the linear range for several reasons. First, this is the highest stiffness range of the cable. As stiffness is a priority in the x-y plane, this alone provides significant motivation to operate in the linear range. Second, analysis and control of linear systems is significantly easier as compared to non-linear systems.

The cable itself determines the amount of tension required to reach the linear range of a cable as well as the value of the stiffness of the cable within the linear range. The elastic stiffness, the weight of the cable, and the length of the cable play a significant role in amount of tension. To complicate things further, the elastic stiffness of the cable is affected not only by the material, but also by the way the fibers are woven within the cable. The cable used will also affect the power requirements for the motors in the cable winders. Some suitable examples for the cables **28**A, **28**B, **28**C, **28**D that can fulfill the requirements of the system **14** include 7×19 steel wire rope and ropes made from ultra-high-molecular-weight polyethylene (UHMWPE) fibers, such as Dyneema® ropes.

For the cables **28**A, **28**B, **28**C, **28**D to operate within the linear range of stiffness, all of the cables **28**A, **28**B, **28**C, **28**D are kept at a predetermined minimum tension. The minimum tension is based on a given cable type and span and is the minimum tension needed to keep the cable in the linear range of stiffness. Therefore, as the end effector **20** is moved and the span of the cables **28**A, **28**B, **28**C, **28**D change, the minimum tension changes.

As mentioned above, for the system **14** of FIG. **5**, there are two tensioning cables **28**C, **28**D that keep all the motion-control cables **28**A, **28**B in tension. This allows for some control of the net tension vector. In the system **14**, the tension of all cables **28**A, **28**B, **28**C, **28**D can be controlled to stay above the minimum tension required to keep them in their linear stiffness range. There can be more than one tensioning solution that meets this requirement. Some tensioning solutions may involve tensions in a few of the cables **28**A, **28**B, **28**C, **28**D that are well above the minimum tension. However, it is not desirable to apply more tension than required. This produces no benefit, and it only serves to increase the required motor power and the required strength of the components of the system **14**. Thus, the system **14** is preferably operated with a tensioning solution that keeps all of the cables **28**A, **28**B, **28**C, **28**D above their minimum tension requirement and has the lowest maximum tension in any one of the cables **28**A, **28**B, **28**C, **28**D from all possible options. The required tension in the tensioner cables **28**C, **28**D will obviously vary as the end effector **20** traverses the 3D workspace W.

FIG. **7** is an isometric view of one embodiment of a base station **22** for the cable-driven additive manufacturing system **14**. The base station **22** of FIG. **7** can include the various functions and components as described in the embodiments of FIGS. **2**-**5**, and like parts will be identified with like numerals. The base station **22** can be a motion-control base station, and in the illustrated embodiment, two adjustable motion-control cables **28**U, **28**L run from the base station **22** to an end effector (not shown). Alternatively, one adjustable cable or three adjustable cables may be associated with the base station **22**, as described above for the previous embodiments. The base station **22** can mobile for transport to and from the worksite, and is configured to be statically arranged about the perimeter of the 3D workspace W during use.

The base station **22** includes one cable winder **40**, and both cables **28**U, **28**L can be adjustably extended from the cable winder **40** and retracted back on the cable winder **40**. A motor **52** or the like can control the cable winder **40**. The motor **52** can be can be in operative communication with a winder motor controller and power supply **54**, which provides power to and control of the winder motor **52** to operate the cable winder **40**. The winder motor controller and power supply **54** can be in operative communication with a central controller as described above

The base station **22** includes one pulley **42**U disposed above the cable winder **40**, and two pulleys **42**M, **42**L disposed below the cable winder **40**. The first or upper motion-control cable **28**U runs from the cord winder **40**, wraps around the upper pulley **42**U, and extends to the end effector. The second or lower motion-control cable **28**L runs from the cord winder **40**, winds around the middle pulley **42**M, wraps around the lower pulley **42**, and extends to the end effector.

The base station **22** can include a support **56** adapted to be statically fixed to the ground or otherwise anchored at the worksite, and a framework **58** extending upwardly from the support **56**. The framework **58** can include a support surface **60** for the cable winder **40** and pulleys **42**U, **42**M, and **42**L. From the pulleys **42**U, **42**M, and **42**L to the end effector, the cables **28**U, **28**L can run generally orthogonally to the support surface **60**.

The base station **22** can be adjustable to allow the end effector to print taller structures without interfering with the cables **28**U, **28**L. As described above, generally, the point at which the cables **28**U, **28**L extend in the x-y plane away from the base station **22** needs to be able to raise up as the printed structure gets taller. In one embodiment, at least a portion of the base station **22** can telescope to raise the pulleys **42**U, **42**M, and **42**L. For example, the support surface **60** can be a telescoping support surface **60**, the framework **58** can be a telescoping framework **58**, or the support **56** can telescope or be otherwise adjustable.

The base station **22** can optionally include a cable winder **50** for a suspension cable **30** used to adjust the position of an aerial hoist **18** (FIG. **8**). The suspension cable **30** can be adjustably extended from the cable winder **50** and retracted back on the cable winder **50**. A motor **62** or the like can control the cable winder **50**. The motor **62** can be can be in operative communication with a winder motor controller and power supply **64**, which provides power to and control of the winder motor **62** to operate the cable winder **38**. The winder motor controller and power supply **64** can be in operative communication with a central controller as described above.

The cable winder **50** can be supported on the framework **58**, or elsewhere on the base station **22**. In the illustrated embodiment, the cable winder **50** is disposed on second support surface **66** of the framework **58**, which is disposed rearwardly of the first support surface **60**. The base station **22** can include at least one pulley **68**, or another suitable cable guide, which routes the suspension cable **30** around the framework **58** or another portion of the base station **22** to reach the cable winder **50**.

FIG. **8** is an isometric view of one embodiment of an aerial hoist **18** for the cable-driven additive manufacturing system **14**. The aerial hoist **18** of FIG. **8** can include the various functions and components as described in the embodiments of FIGS. **2**-**5**, and like parts will be identified with like numerals. In the illustrated embodiment, one adjustable suspension cable **30** runs from a base station **22** (FIG. **7**), through the aerial hoist **18** to an end effector (not shown). The suspension cable **30** can be adjustably extended from and retracted back on a cable winder **50** (FIG. **7**) on the base station **22**. Alternatively, more than one adjustable suspension cable may be associated with the aerial hoist **18**, as described above for the previous embodiments.

The aerial hoist **18** can suspended by existing construction equipment, such as a conventional crane **24** (FIG. **2**). The aerial hoist **18** forms an apex of the cable configuration for the cable-driven system. The aerial hoist **18** can include a framework **70** that is hung from the crane **24** by a connector **72**. Springs **74** can be provided between the connector **72** and the framework **70** to provide compliance between the aerial hoist **18** and the crane **24**, which may sway during operation, and to prevent the crane **24** from pulling up too hard on the aerial hoist **18**. Guy-wire connectors **76** are provided on the framework **70** for securing the aerial hoist **18** with guy-wires (not shown).

The aerial hoist **18** includes two pulleys **48**U, **48**L or other suitable cable guides that route the suspension cable **30** to change the direction of the force applied by the cable **30**. The suspension cable **30** runs from the base station **22** (FIG. **7**), winds around the lower pulley **48**L, wraps up and around the upper pulley **48**U, and extends down to the end effector. Rollers **78** can frictionally engage the cable **30** to keep the cable **30** engaged with the upper pulley **48**U. The framework **70** can support the pulleys **48**U, **48**L and the rollers **78**. It is noted that in FIG. **8**, a portion of the framework **70** is illustrated in phantom line for clarity.

There are several advantages of the present disclosure arising from the various aspects or features of the apparatus, systems, and methods described herein. For example, the various embodiments of the additive manufacturing systems and methods disclosed herein can be employed at large-scale work sites without requiring massive equipment and machinery. The cable-driven system does not require the same level of site preparation as gantry-based systems. With the cable-driven system disclosed herein, cable winders can be placed around the worksite via the base stations. This does not require leveling of the site, and can be implemented on a wide variety of terrain. Furthermore, the base stations are small compared to the work site leaving more open space available for construction and the maneuvering of equipment and workers. Still further, the cable-driven system disclosed herein integrates with existing construction equipment.

Another advantage of the various embodiments of the additive manufacturing systems and methods disclosed herein is the single lift point or aerial hoist. Most cable driven robots have cable winders at multiple aerial points. In a situation where the robot is permanently installed in a building or high-bay, this not a problem as these winders can be affixed to a large frame or to the columns of the building itself. However, in an outdoor fieldable platform this is less practical. The cable-driven system disclosed herein has an aerial hoist suspending by existing construction equipment, namely a crane, or a balloon. Implementing a crane suspended system will allow for much quicker machine set up and versatility in construction site location.

Yet another advantage of the various embodiments of the additive manufacturing systems and methods disclosed herein is that the crane or other suspender acting as a static hoist point for the system does not need to have high rigidity, it only needs to supply sufficient upward force. Conventional cranes are not rigid; rather they have a fairly low effective spring rate and so would be unsuitable to use with prior additive manufacturing systems which require rigidity. In contrast, the various embodiments of the additive manufacturing systems and methods disclosed herein can be with a crane, a lighter-than-air balloon, the roof of an inflatable building, or other systems without high rigidity but which provide sufficient upward force for the system.

The above description is that of current embodiments of the invention. Various alterations and changes can be made without departing from the spirit and broader aspects of the invention as defined in the appended claims, which are to be interpreted in accordance with the principles of patent law including the doctrine of equivalents. This disclosure is presented for illustrative purposes and should not be interpreted as an exhaustive description of all embodiments of the invention or to limit the scope of the claims to the specific elements illustrated or described in connection with these embodiments. The present invention is not limited to only those embodiments that include all of these features or that provide all of the stated benefits, except to the extent otherwise expressly set forth in the issued claims. Any reference to claim elements in the singular, for example, using the articles "a," "an," "the" or "said," is not to be construed as limiting the element to the singular. The technology disclosed and claimed herein may be available for licensing in specific fields of use by the assignee of record.

The invention claimed is:

1. A cable-driven additive manufacturing system comprising:

an end effector configured for linear translation within a three-dimensional workspace along an x-axis, a y-axis, and a z-axis;

an aerial hoist suspending the end effector within the three-dimensional workspace by at least one suspension cable, the aerial hoist having a static position within the three-dimensional workspace whereby the aerial hoist is not translated along the x-axis with the end effector and the aerial hoist is not translated along the y-axis with the end effector;

an aerial cable winder configured to control linear translation of the end effector along the z-axis;

a plurality of motion-control base stations disposed below the aerial hoist and configured to control linear translation of the end effector in an x-y plane defined by the x-axis and the y-axis, each motion-control base station comprising a base station cable winder;

a plurality of motion-control cables, at least one of the plurality of motion-control cables running from each of the base station cable winders to the end effector;

at least one tension-control base station; and

at least one tension-control cable running from the tension-control base station to the end effector.

2. The additive manufacturing system of claim **1**, wherein the plurality of motion-control base stations comprises at least two motion-control base stations.

3. The additive manufacturing system of claim **2**, wherein the at least one tension-control base station comprises a first tension-control base station and a second tension-control base station spaced from the first tension-control base station, and the at least one tension-control cable comprises a first tension-control cable running from the first tension-control base to the end effector and a second tension-control cable running from the first tension-control base to the end effector.

4. The additive manufacturing system of claim **1**, wherein the plurality of motion-control cables and the at least one tension-control cable are tensioned to lie substantially parallel to the x-y plane.

5. The additive manufacturing system of claim **4**, wherein the at least one suspension cable includes at least a portion extending along the z-axis.

6. The additive manufacturing system of claim **1**, wherein at least one of the plurality of motion-control base stations comprises a pulley supporting the associated motion-control cable to change the direction of the force applied by the associated motion-control cable.

7. The additive manufacturing system of claim **6**, wherein the at least one of the plurality of motion-control base stations comprises a telescoping portion to adjust the height of the pulley.

8. The additive manufacturing system of claim **1**, wherein at least one of the plurality of motion-control base stations comprises two motion-control cables running to the end effector, wherein the two motion-control cables are parallel to each other.

9. The additive manufacturing system of claim **8**, wherein at least one other of the plurality of motion-control base stations comprises three motion-control cables running to the end effector, wherein the three motion-control cables are parallel to each other.

10. The additive manufacturing system of claim **9**, wherein the at least one suspension cable comprises a single suspension cable.

11. The additive manufacturing system of claim **1**, wherein the aerial hoist comprises a platform which supports the aerial cable winder, and the end effector is suspended from the platform by the at least one suspension cable, wherein the at least one suspension cable can be adjustably extended from the aerial cable winder on the platform and retracted back on the aerial cable winder on the platform.

12. The additive manufacturing system of claim **11**, wherein the at least one suspension cable comprises at least two suspension cables suspending the end effector below the platform.

13. The additive manufacturing system of claim **1**, wherein the aerial hoist comprises a pulley supporting the at least one suspension cable to change the direction of the force applied by the at least one suspension cable.

14. The additive manufacturing system of claim **13**, wherein the aerial cable winder is provided on one of the plurality of motion-control base stations or on the at least one tension-control base station, wherein the at least one suspension cable can be adjustably extended from the aerial cable winder and retracted back on the aerial cable winder.

15. The additive manufacturing system of claim **1**, wherein the aerial hoist comprises a single aerial hoist configured to be suspended by a crane.

16. The additive manufacturing system of claim **1**, further comprising at least one guy-wire extending between the aerial hoist and each of the plurality of motion-control base stations and the at least one tension-control base station.

17. The additive manufacturing system of claim **16**, wherein each motion-control base station and the at least one tension-control base station comprises a guy-wire cable winder, wherein each of the guy-wires can be adjustably extended from their respective guy-wire cable winder and retracted back on their respective guy-wire cable winder.

18. The additive manufacturing system of claim **1**, wherein the system is operated to maintain the plurality of motion-control cables in a linear range of stiffness in which the contribution of catenary sag of the plurality of motion-control cables becomes negligible and the stiffness remains approximately constant with increasing tension.

19. The additive manufacturing system of claim **18**, wherein the plurality of motion-control cables are tensioned to at least a predetermined minimum tension comprising a minimum tension at which cable stiffness remains approximately constant with increasing tension.

20. The additive manufacturing system of claim **18**, wherein at least one of the plurality of motion-control cable comprises one of a 7×19 steel wire rope and a rope made from ultra-high-molecular-weight polyethylene fibers.

* * * * *

UNITED STATES PATENT AND TRADEMARK OFFICE

CERTIFICATE OF CORRECTION

PATENT NO. : 11,230,032 B2
APPLICATION NO. : 16/383105
DATED : January 25, 2022
INVENTOR(S) : Brian K. Post et al.

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

In the Claims

Column 14, Claim 20, Line 36:
"cable" should be -- cables --

Signed and Sealed this
Twenty-second Day of March, 2022

Drew Hirshfeld
Performing the Functions and Duties of the
Under Secretary of Commerce for Intellectual Property and
Director of the United States Patent and Trademark Office